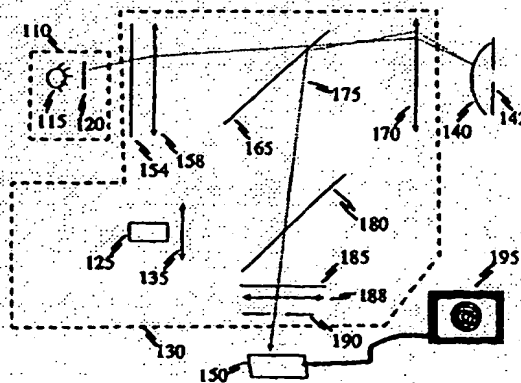PCT   WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: METHOD AND APPARATUS FOR MEASURING PROPERTIES OF THE EYE USING A VIRTUAL IMAGE

(57) Abstract

A technique for evaluating the topography of a cornea (140) is disclosed, which utilizes a virtual image of a keratoscope pattern. The disclosed topography system includes a structured light source (110) to create the keratoscope pattern (5) or another diagnostic pattern, an optical assembly (130) to focus the created pattern upon or behind the cornea (140), and for capturing the image reflected off the patient's eye and directing the reflected image toward in imaging system (150, 195) for processing. Light emitted by the light source (110) is preferably not in the visible range to minimize discomfort to the patient. Since the topography is evaluated with a projected virtual image, there is no nose or brow shadow, thereby allowing better corneal coverage. The optical system includes an aperture stop (190) which is approximating the center of a normal cornea (140). Thus, wide angle capture is achieved as reflected rays reaching the imaging system (150, 195) appear as if they originated at the center of the cornea (140). A pupil detection mechanism is disclosed which is performed independently of the diagnostic pattern illumination, thereby facilitating pupil detection. In an alternative embodiment, the diagnostic pattern is generated using a variable light pattern generator, which provides diagnostic abilities. The disclosed topography system may be reconfigured to serve as a visual field measuring device, or a perimeter.

METHOD AND APPARATUS FOR MEASURING
PROPERTIES OF THE EYE USING A VIRTUAL IMAGE

CROSS-REFERENCE TO RELATED APPLICATION

This is a continuation-in-part of U.S. Patent Application No. 08/695,616, filed August 12, 1996, entitled "Method and Apparatus For Measuring Properties of The Eye Using A Virtual Image," which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to a device for evaluating the curvature or shape of the cornea of the eye, and more particularly, to a corneal measurement device that assists with pre-operative or post-operative measurements of the cornea, with contact lens fitting and with the diagnosis of diseases of the cornea.

BACKGROUND OF THE INVENTION

The cornea, being the front surface of the eye, provides its major refracting surface and is important to quality vision. Recently, a number of corneal surgical techniques have been developed for correcting visual deficiencies, such as near-sightedness, far-sightedness and astigmatism. In order to assist with such surgical techniques, a number of devices have been proposed or developed to evaluate the topography, i.e., the shape or curvature, of the cornea. In addition, such corneal topography techniques are useful for fitting contact lenses and for the diagnosis and management of corneal pathologic conditions, such as keratoconus and other ectasias. For example, prior to performing a corneal surgical technique to correct a refractive error, the patient is preferably screened using a corneal topography device to rule out the possibility of subclinical keratoconus.

Corneal topography is typically measured using a series of concentric lighted rings, known as a keratoscope pattern 5, shown in FIG. 1. In one typical embodiment, shown in FIG. 2, keratoscope pattern 5 is created by a keratoscope target 10, consisting of illuminated concentric rings which emit light rays which are projected onto the cornea of a patient's eye 15. Light rays 12, 20 are reflected off patient's cornea 15, and a portion of light ray 20 is captured by an objective lens 25 and focused onto an imaging system 30, such as a video camera. A computer 35 is utilized to compare the image captured on imaging system 30 with a stored reference pattern, or other known information, to identify any distortions in the captured image and thus calculate any deformations in the patient's cornea.

While conventional corneal topography devices have achieved significant success, such devices suffer from a number of limitations, which, if overcome, could significantly enhance their accuracy and utility. In particular, earlier designs for topography devices have incorporated large keratoscope targets, causing the overall size of the prior art devices to be quite large. In an operating room or a doctor's office, however, where space is at a premium, it is desirable to minimize the overall size of the topography device.

In addition, commercially available topography devices, such as the design illustrated in FIG. 2, typically measure the topography of only a relatively small area of the cornea. For example, in the design shown in FIG. 2, the light beam is emitted from a large, flat, backlit keratoscope target 10 and is then reflected off cornea 15. Thereafter, a portion of light 20 reflected off cornea 15 is focused by small objective lens 25 at the center of keratoscope target 10 onto imaging system 30, such as a CCD chip. Additional light rays 12 reflected from the peripheral portions of cornea 15, however, are not captured by objective lens 25 and are therefore not imaged onto imaging system 30. Therefore, such prior art devices are unable to measure the peripheral cornea.

To overcome this problem, prior art devices have attempted to capture the light rays reflected from the peripheral portions of cornea 15 by designing a keratoscope target 10' in the shape of a cylinder or cone, as shown in FIG. 3, encompassing the peripheral cornea. In this manner, light rays emitted by cylindrical or conical keratoscope target 10' will form a pattern 5 of illuminated rings which will be reflected off cornea 15. The reflected light rays, including light rays reflected off the peripheral portions of cornea 15, will be captured by objective lens 25 and imaged onto imaging system 30. To be effective, however, cylindrical or conical keratoscope target 10' must be positioned very close to the eye, and thereby tends to impinge on the patient's brow and nose. In addition to being potentially uncomfortable and potentially contributing to the spread of disease, the close approach of keratoscope target 10' makes the design very error-prone, as a slight error in alignment or focusing causes a large percentage change in the position of the keratoscope rings relative to the eye.

In addition, current systems tend to provide poor pupil detection and do not accurately measure non-rotationally symmetric corneas, such as those with astigmatism. The location of the pupil is particularly important in planning surgical procedures for correcting visual deficiencies. In current systems, pupils are typically detected by deciphering the border of the pupil from the image of the keratoscope rings. This is particularly difficult with conventional designs, however, as the intensity transition from the black pupil to a dark iris is minimal compared to the intensity transition from a bright keratoscope ring image to a dark interring spacing. As a result, the pupil detection algorithms in current systems often fail.

Furthermore, current systems have difficulty detecting the edges of the keratoscope rings and difficulty separating ring images from background iris detail. Conventional corneal topography systems image the iris along with the keratoscope rings. Particularly in patients having light-colored irises, however, the bright reflection from iris detail obscures the rings, thereby making detection of ring edges difficult. Finally, conventional devices utilize high intensity visible light to illuminate the

keratoscope target and therefore cause discomfort to the patient. The high intensity light is required because relatively little light is actually reflected from the cornea and captured by the measuring devices.

5

As is apparent from the above discussion, a need exists for a more compact corneal topography device. Another need exists for a topography system that allows a large area of corneal coverage without the focusing problems and invasive approach of previous designs. A further need exists for a system incorporating improved pupil detection by using an image that does not include the keratoscope rings. Yet another need exists for a topography device providing improved separation of the corneal reflection of the keratoscope pattern from the iris detail. A further need exists for a topography system utilizing light levels that are not unpleasant for the subject undergoing measurement. An additional need exists for a topography device that permits accurate measurement of non-rotationally symmetric corneas, such as those with astigmatism.

20

Summary of the Invention

Generally, according to aspects of the present invention, a method and apparatus for measuring the topography of the cornea are provided. The method and apparatus utilize a virtual image of a keratoscope pattern or other diagnostic pattern, which is projected at a desired distance in front of the patient's eye. Since the topography is evaluated with a virtual image, there is no nose or brow shadow, allowing better coverage of the cornea and providing a design which is relatively insensitive to focusing errors.

30

In certain embodiments, however, it has been found preferable to position the virtual image of the keratoscope pattern at some other location. For example, a virtual image of the keratoscope pattern may be formed just behind the cornea such that after being reflected from the surface of the cornea is re-imaged just in front thereof. Likewise, however, distortions in the cornea are observed in the reflected real image of the keratoscope pattern.

The disclosed topography system includes a structured light source, preferably consisting of an illumination source and a beam modulating system, to create the keratoscope pattern or other desired diagnostic pattern. In order to minimize discomfort to the patient, light emitted by the illumination source is preferably not in the visible range. In addition, the illumination source is preferably monochromatic.

In accordance with an aspect of the present invention, the beam modulating system may be embodied as a photographic slide film consisting of opaque markings on a transparent background, or a variable light pattern generator, such as an array of liquid crystal pixels, or an array of light emitting diodes. In this manner, the beam modulating system can provide flexibility in selecting pattern images to achieve various diagnostic abilities.

An optical assembly focuses the created pattern upon the cornea, and thereafter captures the image reflected off the patient's eye and directs the reflected image toward an imaging system, such as a CCD, for processing. According to a feature of
5 the invention, the optical assembly preferably includes means for preventing scattered light reflected from the patient's iris from being imaged by the CCD. In one embodiment, a pair of polarizing filters having the same polarization attenuate the scattered light reflected from the patient's iris, thereby permitting a clean image
10 of the keratoscope pattern, as reflected off the patient's cornea, on the CCD camera.

According to a further feature of the invention, the optical system achieves wide angle capture by including an aperture stop
15 which is preferably conjugate with a point behind the corneal surface approximating the center of curvature of a normal cornea. Thus, reflected rays reaching the imaging system appear as if they originated at the center of curvature of the cornea.

20 The corneal topography device preferably includes a centration illumination source and a focusing laser which are utilized to center and focus the corneal topography system relative to the patient's cornea. During the centration and focusing operation, the structured light source used to generate the diagnostic pattern
25 is preferably not illuminated. Thus, pupil detection is facilitated, since the pupil boundaries are not obscured by one or more rings of the keratoscope pattern.

In accordance with a further aspect of the invention, a method
30 of calibrating the corneal topography device is disclosed. The method comprises the steps of: positioning a calibration sphere approximating the size of a cornea at a desired focal point; illuminating the calibration sphere with a diagnostic pattern; creating a first image on an imaging system of a reflection of the
35 diagnostic pattern off the sphere; positioning a cursor on the imaging system at approximately the center of the first image; creating a second image on the imaging system of a reflection of a centration illumination source off the sphere; adjusting the position of the centration illumination source so that the second
40 image is approximately centered around the previously positioned cursor; and storing the first image as a reference image for calculating topographical information about an unknown cornea.

Yet another aspect of the invention allows the disclosed
45 topography system to be reconfigured as a perimeter to evaluate a patient's field of vision. When configured as a perimeter, the structured light source is preferably embodied as a backlit liquid crystal array, a cathode ray tube or an array of light emitting diodes. To measure the patient's visual field, the patient
50 observes a virtual image of the pattern produced by the structured light source, which is projected at a distance in front of the patient's eye. In addition, an infrared laser illuminates the patient's pupil with an infrared beam. A reflection of the infrared beam scattered off the patient's iris is imaged on the

CCD.

   According to a further feature of the invention, the optical
system includes means for attenuating light which is reflected off
5 the patient's cornea during the visual field measurement, such as
a pair of perpendicular polarizers positioned in the optical path.
The system monitors fixation by tracking the movement of the pupil,
using the scattered infrared image. When the center of the pupil
moves beyond a predefined threshold, an alarm indicates when
10 fixation is lost.

   Brief Description of the Drawings
   A more complete understanding of the present invention, as
well as further features and advantages of the invention, will be
15 obtained by reference to the detailed description and drawings.

   FIG. 1 is a diagram illustrating a keratoscope pattern of the
prior art;
   FIG. 2 is a block diagram illustrating the optical arrangement
20 of a prior art topography device;
   FIG. 3 is a block diagram illustrating the optical arrangement
of an alternative prior art topography device design;
   FIG. 4 is a block diagram of a corneal topography device
incorporating features of the present invention;
25   FIG. 5 illustrates the location of real and virtual images of
the keratoscope pattern in the embodiment of FIG. 4;
   FIG. 6 is an enlarged view of a method of wide angle capture
of a virtual image, according to a feature of the present
invention;
30   FIG. 7 illustrates the corneal topography device of FIG. 4 in
operation during focusing and centration;
   FIG. 8A illustrates an alternative keratoscope pattern for use
with the present invention;
   FIG. 8B illustrates another alternative keratoscope pattern
35 for use in the present invention;
   FIG. 9 illustrates yet another alternative keratoscope pattern
for use with the present invention;
   FIG. 10 illustrates the corneal topography device of FIG. 4
reconfigured as a perimeter to measure a patient's visual field;
40   FIG. 11 is a block diagram of another embodiment of a corneal
topography device incorporating features of the present invention;
and
   FIG. 12 is a graph showing the location of the exit pupil in
the device of FIG. 11 as a function of the base radius of curvature
45 of the cornea.

   DETAILED DESCRIPTION
   As shown in FIG. 4, a corneal topography device according to
the present invention includes a structured light source 110, for
50 creating a diagnostic pattern, such as keratoscope pattern 5 (FIG.
1), and an optical assembly 130 for focusing the created pattern
5 upon cornea 140 of a patient's eye and for capturing the pattern
reflected off the patient's eye and directing the reflected pattern
toward an imaging system 150, such as a CCD chip or other imaging

sensor, including CMOS devices, for further processing. Structured light source 110 preferably consists of an illumination source 115 and a beam modulating system 120 for creating keratoscope pattern 5, as illustrated in FIG. 1, or an alternate pattern as discussed
5   below. In one embodiment, structured light source 110 includes a diffuser to spread out the light.

According to one feature of the invention, light emitted from illumination source 115 is preferably not in the visible range,
10 thereby minimizing the discomfort to the patient resulting from the high intensity source. In one embodiment, beam modulating system 120 for creating keratoscope pattern 5 is embodied as photographic slide film consisting of opaque markings on a transparent background.
15

As shown in FIG. 4, optical assembly 130 preferably includes, in sequence, a polarizing filter 154, a focusing lens 158, for capturing and directing the polarized light upon a beam splitter 165 and an objective lens 170, which focuses keratoscope pattern
20 5 upon cornea 140. In addition, light 175 reflected from cornea 140 is captured by objective lens 170 and is then reflected by beam splitter 165 toward a second beam splitter 180. The light passes through beam splitter 180, in a known manner, and through polarizing filter 185, which is oriented parallel to polarizing
25 filter 154. Thereafter, the light passes through a focusing lens 188, which serves to direct the reflected pattern through an aperture stop 190, such as an adjustable round hole or an iris, and onto CCD chip 150. CCD chip 150 transmits the captured image to a personal computer 195, or another processor, where the image of
30 the reflected pattern is displayed on a computer screen for further evaluation by an operator.

According to a further feature of the invention, polarizing filter 185, having the same polarization as polarizing filter 154,
35 serves to prevent scattered light reflecting from the patient's iris 142 from being imaged on CCD chip 150. In this manner, scattered light reflected from patient's iris 142 is attenuated, permitting a clean image of the keratoscope pattern, as reflected off cornea 140, on the CCD camera, without noise and background
40 detail from patient's iris 142, thereby simplifying image processing.

In addition, the corneal topography device includes a centration illumination source 125 and a collimating lens 135, and
45 a focusing laser 155, discussed further below in conjunction with FIG. 7, which are utilized during a centration and focusing process to center and focus the corneal topography system relative to patient's cornea 140. In a further embodiment, discussed below in conjunction with FIG. 10, the topography device may be configured
50 as a perimeter to evaluate the patient's field of vision. When configured as a perimeter, centration illumination source 125 preferably emits light in the infrared range.

As the light beam passes from beam modulating system 120

through the various elements of optical system 130 to CCD chip 150,
several images, including real images and virtual images, of the
keratoscope pattern are created, as illustrated in FIG. 5. Image
KI1 is a real image of keratoscope pattern 5 created by focusing
5 lens 158 and lying inside the focal point of objective lens 170.
In a real image, all the light from a point on the pattern passing
through the optical system, actually passes close to or through a
point on the image. In other words, because KI1 is a real image,
keratoscope pattern 5 could actually be seen on a piece of paper,
10 if a piece of paper were inserted into the optical assembly at the
location of KI1.

In addition, objective lens 170 projects image KI1 to create
a virtual image KI2 of keratoscope pattern 5, preferably lying
15 approximately 0.3 meters in front of the patient's eye and being
approximately 0.4 meters in diameter. In a virtual image, rays of
light only appear to diverge from a particular location, without
actually being focused there. In other words, when a patient looks
into objective lens 170, a virtual image KI2 of keratoscope pattern
20 5 appears to be emanating from the location of the virtual image.

Upon looking into objective lens 170, patient's cornea 140
will reflect the perceived virtual image KI2 and create a second
virtual image KI3, located approximately 4 mm behind the cornea 140
25 in the illustrative embodiment. The virtual image KI3 is captured
by objective lens 170 and focusing lens 188, which cooperate to
create a real image KI4 of the virtual image KI3 on CCD 150.

Thus, according to a feature of the invention, a virtual image
30 KI2 of keratoscope pattern 5 is created at a desired distance in
front of the patient's eye. Because the distant image is virtual,
there is no nose or brow shadow, allowing better coverage of the
cornea and providing a design which is relatively insensitive to
focusing errors. It has been observed that the accuracy of the
35 present topography system in projecting keratoscope pattern 5 on
the cornea is determined by the apparent location of the virtual
keratoscope image KI2, rather than by the actual location of
objective lens 170 in relation to the eye. Thus, the present
invention provides a design that is relatively insensitive to
40 focusing, in a similar manner to the prior art design discussed
above in conjunction with FIG. 2, as well as exhibiting improved
corneal coverage, in a manner similar to the prior art design
discussed above in conjunction with FIG. 3.

45 According to a further feature of the invention, measurement
of a large area of the cornea is facilitated by incorporating wide
angle capture of the reflected virtual image KI3. As shown in FIG.
6, a light ray 200 from the virtual keratoscope pattern image KI2
travels through objective lens 170 and strikes cornea 140 at an
50 angle that is nearly perpendicular to the corneal surface. Light
ray 200 is thereafter reflected back from the cornea along a path
210 nearly parallel to the incoming ray 200 from the virtual image
KI2 of keratoscope pattern 5. Aperture stop 190 (FIG. 5) is
preferably conjugate through objective lens 170 and focusing lens

188 with a point approximately 7.8 mm behind the corneal surface, corresponding to the center of curvature of a normal cornea, creating a real image AI of aperture stop 190, approximately at the center of curvature of the cornea, as shown in FIG. 6.

5

This optical configuration ensures that each bright region of the keratoscope pattern substantially illuminates only a corresponding region of the cornea. This is in contrast to the prior art, wherein the bright regions of the keratoscope pattern

10 diffusely illuminate the entire cornea and iris, thereby causing a significant reduction in image contrast. In the present invention, light rays originating from each portion on the keratoscope pattern reaching the corneal surface subtend a substantially small solid angle due to the high f-number of the

15 optical system. As such, the illumination is well controlled, thereby avoiding illuminating those regions of the iris corresponding to the dark regions of the keratoscope pattern. Advantageously, this significantly enhances the image contrast and thus the image quality.

20

Furthermore, this configuration also ensures that a ray that reaches CCD chip 150 was reflected nearly back along incident ray 200, as if emerging from the aperture image AI, thereby allowing a large area of corneal coverage with a target at a significant

25 (virtual) distance from the eye. In other words, this limits reflected rays reaching CCD chip 150 to those rays that reflect as if they originated at the center of curvature of a normal cornea, creating the wide angle capture that characterizes this system. In this manner, the ray reflected off cornea 140 can be reflected

30 at a wide angle and still be captured by the large objective lens. In an alternate embodiment (not shown), aperture stop 190 can be positioned in the optical path between focusing lens 158 and objective lens 170, but still conjugate to the center of curvature of a normal cornea through objective lens 170. In this alternate

35 embodiment, the rays emerging from KI2 are directed toward the image AI of aperture stop 190, so wide angle capture of KI3 is still achieved.

In order to achieve the parameters associated with the

40 illustrative embodiment, namely, so that the center of aperture stop 190 is approximately conjugate to the center of a typical cornea (having a radius of 7.8 mm), and to place the virtual image at a distance of approximately 0.3 m in front of the cornea with a diameter of approximately 0.4 m, objective lens 170 should have

45 a diameter of approximately 5.5 cm and an f-number of approximately 0.7. In addition, objective lens 170 should be positioned approximately 2 cm from the corneal surface.

CENTRATION AND FOCUSING

50 In order to achieve proper centration and focus of the corneal image, the operator preferably watches a video image of the patient's eye on the computer screen while adjusting the position of the corneal topography device relative to the eye in three dimensions. As shown in FIG. 7, during the centration and focusing

operation, centration illumination source 125 and focusing laser 155 are preferably simultaneously illuminated, while illumination source 115 is not illuminated. Light rays 240, 245 emitted from centration illumination source 125 pass through collimating lens 135 and reflect off beam splitter 180 and beam splitter 165. Light rays 240, 245 pass through objective lens 170 and a portion of rays 240 reflect off the cornea, while another portion of rays 245 pass through cornea 140 and are reflected off patient's iris 142.

Rays 240 reflected off the cornea are captured by objective lens 170, reflect off beam splitter 165, are transmitted by beam splitter 180 and are imaged by CCD chip 150. Rays 240 create an image on CCD 150 of centration illumination source 125 that is reflected from the patient's cornea. Meanwhile, the remaining light rays 245 which pass through cornea 140 and are reflected off patient's iris 142, are captured by objective lens 170, are reflected by beam splitter 165 and imaged onto CCD chip 150. Rays 245 thereby create an image of the subject's iris 142 and pupil on the CCD chip. Thus, during the centration process a composite image of the patient's iris, pupil and the reflection of illumination source 125 is created on the CCD chip.

The operator observes the composite image on the display and judges the degree of centration of the reflected image of illumination source 125, for example, with respect to a crosshair or other fixed reference mark on the display to ensure that the topography device is in a proper centered position relative to the patient's cornea.

Simultaneously with centration, focusing laser 155, such as a laser diode, is preferably obliquely illuminating the cornea with a laser beam 247. Most of laser beam 247 will pass through the nearly transparent cornea, and fall harmlessly against patient's iris 142. A small percentage of laser beam 247, however, will be scattered by the cornea. The scattered beam 248 is collected by objective lens 170, is reflected by beam splitter 165 and is imaged onto CCD chip 150. The operator moves the corneal topography device closer or farther from the patient's cornea to align the image of scattered beam 248 with the same reference mark used for centration. When the reflection of centration illumination source 125 and the image of focusing laser 155 are properly aligned, the operator activates a switch to measure the topography. Those skilled in the art will readily note that properly positioning the topography device is necessary to accurately determine the base radius of curvature of the cornea.

Alternatively, a portion of laser beam 247 reflected off the cornea is imaged onto a linear position detector (not shown) that generates a signal proportional to the position of the reflected beam. Of course, other position detectors may be used, such as quadature position detectors or two-dimensional position detectors. It should be understood that when the reflected beam is appropriately centered on the linear position detector, the device is designed such that the cornea is in proper focus. Otherwise,

keratoscope pattern image is thereafter compared to the stored reference image to yield information about the corneal topography, in a known manner.

It should be understood that on a smooth surface the radius of curvature may be dependent on the direction the measurement was made. As such, a surface may have many different radii of curvature. There are, however, typically a maximum and a minimum radius of curvature along directions perpendicular to one another. In mathematics, the product of the maximum and minimum radii of curvature is referred to as the "Gaussian curvature."

It is contemplated that the Gaussian curvature at each point on the cornea may be calculated from the reflected keratoscope pattern, and displayed using, for example, pseudo-coloring. Such information may be useful to surgeons inasmuch as it is typically unchanged by certain surgical procedures, such as astigmatic keratotomy. Furthermore, it may be useful in analyzing the regularity and distribution of transplanted corneal tissue.

Alternatively, other mathematical derivatives of the Gaussian curvature may be used, such as the square root, or inverse of the Gaussian curvature. Similarly, various other approximations to the Gaussian curvature may be used. For example, one approximation is simply multiplying the radii of curvature taken along two perpendicular directions, such as along the sagittal and tangential directions.

CALIBRATION

To calibrate the invention, a calibration sphere (not shown) having a radius of approximately 7.8 mm, to approximate the size of a normal cornea, is positioned, for example, with a bracket that fits objective lens 170 and holds the calibration sphere at the desired focal point. Calibration proceeds in three steps. First, the operator illuminates illumination source 115 and positions a cursor on the computer screen on the middle of the captured image KI4 of keratoscope pattern 5. Next, centration illumination source 125 is illuminated, and its position is adjusted manually so its reflected image on the computer screen is centered around the cursor. Finally, the image KI4 of the reflection of keratoscope pattern 5 off the calibration sphere is stored, thereby providing the necessary reference image to calculate the topography of an unknown cornea.

The calibration process involves comparing the known reference radius to the calculated radius for each point on the computer screen. Normally, devices that rely on wide angle optics must contend with significant optical aberrations. The proposed calibration method allows neutralization of aberrations in the system. Each point on the computer screen corresponds to a chief ray emerging in a specific direction from the virtual image of aperture stop 190 at the center of the calibration sphere. An optical aberration will appear in the calibration sphere image as a deviation of a keratoscope ring, or part of a ring, from the

position that would be expected by paraxial optics. When an unknown cornea is imaged, the amount of deviation due to aberrations is unchanged, and can be removed by a subtraction process to yield an aberration-free image from which accurate
5   corneal topography can be calculated.

STRUCTURED LIGHT SOURCE

As previously indicated, the corneal topography system includes structured light source 110 for creating a keratoscope
10   pattern or another desired pattern. Structured light source 110 preferably includes illumination source 115 and beam modulating system 120. Illumination source 115 may be embodied as any light emitting device, including a laser source, a light emitting diode, or an incandescent lamp. The light emitted by illumination source
15   115, as well as by centration illumination source 125, is preferably either naturally monochromatic, as in for example light from a laser, or is made monochromatic by the use of a color filter. In this manner, chromatic aberration, which would normally be expected with the use of low f-number lenses, is minimized.
20

In one embodiment, previously discussed, beam modulating system 120 is embodied as a piece of photographic slide film consisting of opaque markings on a transparent background, to create the desired pattern. Depending on the application, however,
25   it may be desirable for beam modulating system 120 to be embodied as a programmable image quality light pattern generator for creating variable patterns. In a preferred embodiment, programmable light pattern generator 120 is comprised of an array of liquid crystal pixels, capable of selectively blocking incident
30   light in one mode, i.e., by a scattering or absorption process, and transmitting light in another mode, as is well known to those skilled in the art. In this manner, the liquid crystal array can create a desired pattern by selectively placing each individual pixel of the array in a relaxed (light blocking) state, or in an
35   aligned (light transmitting) state, or in an intermediate state between the two extreme positions, according to a "gray scale." The pixels of the liquid crystal array are preferably selectively energized via a driver which may be controlled by computer 195.

40   In an alternate embodiment, structured light source 110 may be embodied as an array of light emitting diodes (LEDs), a cathode ray tube (CRT) or as a laser controlled by an X-Y galvanometer or scanner or any other light generating or transmitting display. In each of these alternate embodiments, an additional illumination
45   source is not required. In a further, less complex, embodiment, alternate patterns can be achieved, for example, by incorporating a rotatable pattern wheel, with a plurality of selectable positions each creating a unique pattern.

50   ## ALTERNATE PATTERNS
It has been observed that by modifying the conventional keratoscope pattern, additional or more accurate information can be obtained about the corneal topography. In particular, in order to enhance detection and measurement of non-rotationally symmetric

corneas, such as those with astigmatism, a keratoscope pattern which permits identification of the meridian of origin of the reflected ray is preferably utilized. If a particular cornea being evaluated is not rotationally symmetric, angularity will be

5   introduced in the rays reflected from the cornea and the conventional assumption that the target pattern projected through the optical system does not undergo any angular displacement is violated.

10   Thus, according to a further feature of the invention, an enhanced keratoscope pattern, such as pattern 250 illustrated in FIG. 8A, is utilized. Keratoscope pattern 250 of FIG. 8A consists of a plurality of concentric rings 255, 260 as well as a plurality of radial lines 270, 275. In this manner, when the pattern

15   reflected off the patient's cornea is imaged on the CCD chip, the features on each ring allow identification of rays that leave the plane containing the system's primary axis, and the point of reflection from the cornea. By creating features on the target that differentiate segments of each ring, the problem of non-

20   coplanarity of the prior art is solved.

          In variations of this embodiment, circumferential marks, a circular or square checkerboard pattern or a grid of perpendicular lines, for example, may be utilized instead of the radial lines

25   270, 275 to achieve a similar result. For example, a circular checkerboard pattern 295 may be used as illustrated in Fig. 8B. Circular checkerboard pattern 295 consists of concentric circles 296 cut across with radial lines 297 having alternating regions of light and dark. The concentric circles allow the topography to be

30   measured in a manner well known in the art. Furthermore, the radial lines delimited by the regions of light and dark allow the system to identify the plane of origin of the incoming rays from the cornea. This is particularly useful for corneas with astigmatism. Moreover, using alternating regions of light and dark

35   inherently defines the radial lines, reducing the line thickness to zero.

          For measurement of abnormal corneas, such as highly curved or unusually flat corneas, it may be desirable to change the diameter

40   or spacing of the concentric rings on the keratoscope target. Thus, it can be seen that when beam modulating system 120 is embodied as a programmable light pattern generator, such as a liquid crystal array, or as an easily replaceable photographic slide film, in the manner described above, the number of different

45   patterns which can be achieved with the present invention is virtually unlimited. In this manner, the enhanced flexibility in creating patterns provided by the present invention permits greater diagnostic abilities.

50   In addition, the present invention permits the cornea to be initially evaluated with a generic pattern, such as pattern 5 of FIG. 1, and upon detection of certain anomalies, to be further evaluated with an alternate target which has been designed to optimize evaluation of the particular identified anomaly.

        In a further alternate embodiment, a circular pattern 290 may
be utilized to allow calculation of corneal curvature in the
perpendicular directions in a normal cornea (FIG. 9). This permits
the invention to perform ophthalmometry.

                               PERIMETER
        In addition to being useful for evaluating corneal topography,
the present invention may also be utilized as a visual field
measuring device, or a perimeter. Perimetry is an integral part
of general ophthalmic and optometric practice, primarily as an aid
to assessing glaucoma, but also to assess maculopathies and optic
neuropathies. Typically, the visual field of a patient was
evaluated by having the patient view a background, for example, a
projection screen or a CRT, that spans a portion of the patient's
visual field.

        In order to measure a patient's visual field, the optical
system of FIG. 4 is preferably reconfigured as shown in FIG. 10.
The structured light source 110 is preferably embodied as a liquid
crystal display (LCD), a thin film transistor (TFT) LCD display,
a CRT or an array of LEDs, to achieve a moving and changeable
fixation target, or other active matrix display. As indicated by
light ray 176, the pattern created by structured light source 110
is captured by focusing lens 158 and directed through beam splitter
165 and objective lens 170. The objective lens 170 creates a
virtual image of the pattern produced by structured light source
110 that is projected at a preferred distance of 1 meter from the
patient's cornea, and spans at least 25° of the patient's visual
field. During measurement of the patient's visual field, the
patient observes the visual stimulus, namely, the virtual image of
video display 120, by viewing through objective lens 170.

        To measure the patient's visual field, centration illumination
source 125 is preferably embodied as an infrared laser and
illuminates the patient's pupil with an infrared beam 177 through
a polarizing filter 191 and reflected off two beam splitters 180,
165. Infrared beam 177 is scattered off the patient's iris, is
captured by objective lens 170, is reflected off beam splitter 165,
transmitted through beam splitter 180, through a polarizing filter
185 and focusing lens 188 and imaged upon CCD chip 150, for display
on the screen of computer 195. Polarizing filter 185 is oriented
perpendicular to polarizing filter 191, so that scattered light
from the patient's iris is preferentially transmitted, and
reflected light from the cornea is preferentially blocked.

        In operation, the device is centered relative to the patient's
pupil, by centering the video image of the pupil. The system
monitors fixation by tracking the movement of the patient's pupil,
using the scattered infrared image. When the center of the pupil
image moves beyond a predefined threshold, an alarm may be
activated to indicate when fixation is lost. Preferably, beam
modulating system 120 projects a white on gray target of varying
size or luminosity to determine threshold sensitivity at each
point. Targets of varying luminosity are possible by adjusting the

ratio of pixels in the "on" and "off" mode that make up each image.

5   To calculate the position of the pupil in real time, a weighted threshold algorithm is preferably utilized. Initially, the image intensity of all points in the video image is inverted, so that light pixels become dark, and vice versa. This creates a bright pupil on a dark background. Thereafter, all points in the video image with luminance below a predefined threshold are

10   excluded, because they presumably represent iris points. Finally, the unweighted vector center of the remaining points is calculated, representative of the pupillary center.

15   In an alternate embodiment, illumination source 125 is aligned with the patient's visual axis so that a bright image of the pupil appears by reflection from the retina of light from illumination source 125. In this case, thresholding can be performed without inverting the pixel intensities, and the unweighted vector center calculated.

20

In the above embodiments, a virtual image of the keratoscope pattern appears to be located about 30 cm in front of the patient's eye. Such a configuration simulates the function of the keratoscope pattern used in most prior art systems. As discussed

25   above herein, this virtual image is directed to and reflected off the patient's cornea, with distortions in the cornea observed in the reflected image. For some applications, however, it has been found preferable to position the keratoscope pattern at some other location. Although departing from the conventional wisdom, it has

30   been discovered that doing so reduces the complexity and enhances the efficiency of the optical system.

Shown in Fig. 11 is another embodiment of the present invention which is similar to the above embodiments, except that

35   the image of the keratoscope pattern is notably formed at a position not visible as an image to the patient's eye. Contrastingly, in this latter embodiment, a virtual image of the keratoscope pattern is formed just behind the cornea such that after being reflected from the surface of the cornea is re-imaged

40   just in front thereof. Likewise, however, distortions in the cornea are observed in the reflected real image of the keratoscope pattern, which image is then directed onto a CCD, converted into an electrical signal and analyzed by a computer.

45   Referring to this later embodiment depicted in Fig. 11, a beam splitter 1110 is used to direct to the patient's cornea a virtual image of a keratoscope pattern, K_{v1}. Preferably, this keratoscope pattern is created by illuminating a keratoscope target 1115, positioned preferably 4.4 mm inside the front focal plane of a

50   focusing lens 1120, (f=9.5 mm). Alternatively, however, the keratoscope target may be positioned at K_{v1}, but would of course lengthen the optical axis of the system. Incoming light rays emanating from keratoscope target 1115 along an optical axis 1125 pass through an aperture stop 1130 approximately 0.3 mm in

diameter, strike the reflective surface of beam splitter 1110, and then are directed laterally along an optical axis 1135 through aspheric lenses 1140, 1145 onto the surface of a patient's cornea 1150. Preferably, lens 1140 has a focal length of about 74 mm

5 whereas lens 1145 has a focal length of about 46 mm. If desired, beam splitter 1110 may be mounted such that its angle of rotation is adjustable. In the event that the beam splitter becomes misaligned, realignment is then readily possible. Also, pelicles may be used instead of beam splitters.

10

The virtual image of the keratoscope pattern K_{v2} is formed approximately 2.8 mm behind the cornea, with the reflected light therefrom forming an image of a keratoscope pattern K_{r1}, approximately 10.6 mm in front of the cornea (base radius of

15 curvature of 7.8 mm). It is this latter real image that is distorted by any abnormal shape in the cornea. Lenses 1140, 1145 direct the distorted image of the keratoscope pattern, K_{r1}, through optical assembly 1155, consisting of lens 1160 ($\sim f=27$ mm) and lens 1165 ($\sim f=6$ mm), which are separated apart ~ 2.8 mm. This optical

20 assembly then focuses the distorted keratoscope pattern image, K_{r1}, onto a charge coupled device (CCD) 1170, converting the image into a video signal for image processing, such as by a computer. CCD 1170 is positioned about 2.5 mm behind lens 1160.

25 As in the previous embodiment, it should be clearly understood that lenses 1140 and 1145 are specifically designed such that the chief rays from keratoscope target 1115 strike the cornea at an angle substantially perpendicular to the surface thereof. Optical analysis and ray tracing indicate this condition specifically also

30 images aperture stop 1130 near or about the nominal center of curvature of the cornea, which may be approximated as an ellipse having a base radius of 7.8 mm and a conic constant of about 0.25. This latter image of aperture stop 1130 is shown as 1130' in the figure. By imposing this condition and also sufficiently limiting

35 the size of the aperture stop, any light rays reflected from the cornea travel substantially along a path parallel or collinear with the corresponding incident light rays. Preferably, the optical system has a working f-number of approximately 360.

40 This embodiment also uses a unique method of accommodating a wide range of eyes or measuring abnormal corneas. Eyes suffering from keratoconus typically have a small radius of curvature near the center of the cornea, for example, as short as 4 mm. On the other hand, post-refractive surgery eyes may have a radius of

45 curvature as large as 11 mm. Unfortunately, this variation in the radius of curvature shifts the nominal image plane of the keratoscope pattern as well as the image plane of the exit pupil. And, uncorrected may result in an unacceptable image quality. Sufficiently limiting the size of the aperture stop of the optical

50 system, however, compensates for the former inasmuch as it extends the depth of field such that the image remains acceptable, even though the image plane shifts greatly.

With regard to the exit pupil, it has been determined that

allowing the location of the exit plane to move through the plane
of the CCD prohibitively degenerates the image quality. To
compensate for this, it has been found that restricting the exit
pupil to pass through infinity provides an acceptable image, even
5 for wide variations in the shape of the cornea. In order to better
understand this condition, an illustrative graph of the position
of the exit pupil (from the nominal image plane) as a function of
the base radius of curvature of the cornea is shown in Fig. 12.
It should be clearly understood that the nominal image plane is
10 where the image of the reflected keratoscope pattern is formed for
a normal cornea and herein coincident with the plane of the CCD.

First, consider a cornea having a short base radius of
curvature of 4 mm. In this latter instance, exit pupil 1130'' is
15 located a short distance (~2.1 mm) in front of the plane of the
CCD. As the radius of curvature approaches the limiting radius R_o,
the location of exit pupil 1130'' approaches negative infinity.
And, further increasing the radius of curvature shifts the location
of the exit pupil toward the plane of the CCD, but does so from
20 positive infinity, as illustrated. For a normal cornea having a
base radius of curvature of 7.8 mm, exit pupil 1130'' is located
about 26.4 mm behind the plane of the CCD.

In general, the location of the exit pupil satisfies
25 approximately the following equation:

$$L = \frac{C_1}{(R_o - r)}$$

wherein L is the distance of the exit pupil from the plane of the
CCD; R_o is 7.51 and C_1 is -7.55; and r is the base radius of
curvature of the cornea.
30

Thus, it has been found that an optical system as described
above herein is well suited to compensate for variations in the
radius of curvature inasmuch as the location of the exit pupil
never passes through the plane of the CCD. This is so even though
35 the location of the exit pupil shifts from one side of the plane
of the CCD to the other.

In the previous embodiments discussed above herein, fixation
was readily achieved by having the patient look at the center of
40 the keratoscope pattern and as such along the optical axis of the
instrument. It should be recalled, however, that in the present
embodiment the keratoscope pattern is not visible to the patient's
eye, other than as an overall illumination. This is so because the
keratoscope pattern is focused to a point located just behind the
45 patient's cornea. Accordingly, in this embodiment a separate
visible fixation pattern is provided to ensure that the patient's
visual axis is aligned with the optical axis of the instrument.
More specifically, a fixation target 1175 consisting of a clear
glass plate with a small black pattern is positioned within the

back focal plane of the lens system formed by lenses 1140 and 1145.
In this manner, a virtual fixation pattern can be formed at a
distance of about 40 cm in front of the patient's eye. Of course,
the features within the fixation target are judiciously chosen to
5   be large enough for the patient to focus on (~5-10 arc minutes)
when viewing the pattern, but small enough not to block the light
rays reflected from the cornea.

        Similarly, pupil detection may be accomplished using on-axis
10 illumination as described herein above for the previous
embodiments. Likewise, focusing may be accomplished using a
portion of a beam scattered or reflected off the cornea, as
described herein above. It is contemplated, however, that off-axis
illumination may also be used for pupil detection. Referring back
15 to Fig. 11, lenses 1140 and 1145 may be used to image an off-axis
illumination source 1180 to the patient's iris. Radiation
scattered from the iris is likewise collected and imaged onto CCD
1170 so as to detect and locate the edge of the pupil in a manner
described above herein. Off-axis illumination may even be
20 preferable since it prevents specular reflections from the cornea
and retina from interfering with locating the edge of the pupil.

        It is to be understood that the embodiments and variations
shown and described herein are illustrative of the principles of
25 this invention only and that various modifications may be
implemented by those skilled in the art without departing from the
scope and spirit of the invention.

Claims:

1. An apparatus for evaluating the shape of a cornea, said apparatus comprising:
   a structured light source for generating a diagnostic pattern;
   an optical system for projecting a virtual image of said diagnostic pattern at a distance in front of said cornea, capturing a reflection of said virtual image off said cornea, and for redirecting said reflection onto an imaging system; and
   processing means for determining the shape of said cornea by comparing said reflected image detected by said imaging system with stored reference information.

2. The apparatus according to claim 1, wherein said diagnostic pattern is comprised of one or more concentric rings.

3. The apparatus according to claim 2, wherein said diagnostic pattern further comprises means for differentiating segments of said rings.

4. The apparatus according to claim 1, wherein said structured light source is embodied as an illumination source for generating a light beam and a beam modulating system for generating said diagnostic pattern.

5. The apparatus according to claim 4, wherein said beam modulating system is embodied as a liquid crystal array for producing said diagnostic pattern.

6. The apparatus according to claim 4, wherein said beam modulating system is embodied as a programmable light pattern generator capable of producing a plurality of said diagnostic patterns.

7. The apparatus according to claim 4, wherein said illumination source emits non-visible light.

8. The apparatus according to claim 1, wherein said optical system further comprises means for attenuating light scattering off the iris of said eye.

9. The apparatus according to claim 1, further comprising a pupil detection mechanism, wherein said pupil detection mechanism includes an illumination source illuminated independently of said structured light source.

10. The apparatus according to claim 1, wherein the optical system further comprises an aperture stop which is conjugate through the optical system with a point behind the corneal surface, said point corresponding approximately to the center of curvature of a normal cornea, said aperture stop permitting rays of light to reach the imaging system which appear to have originated at said point behind the corneal surface.

11. The apparatus according to claim 1, wherein said optical

system includes an objective lens for projecting said virtual image of said diagnostic pattern, said objective lens being positioned approximately 2 cm from the surface of said cornea.

12. The apparatus according to claim 1, wherein rays of light reflected off the corneal surface and captured by the imaging system appear to emanate from a virtual aperture that is behind the corneal surface.

13. The apparatus according to claim 1, wherein said structured light source is essentially monochromatic.

14. A corneal measuring device including a measuring stimulus, an optical system consisting of optical elements, and an imaging device, wherein a virtual image of the measuring stimulus is projected by the optical elements, wherein light from the virtual image of the measuring stimulus reflects off a cornea and is captured by said imaging device, and wherein the reflected light is analyzed to determine the shape of the cornea.

15. An apparatus for evaluating the visual field of a patient, said apparatus comprising:
   a light pattern generator for generating a visual stimulus;
   an optical system for projecting a virtual image of said visual stimulus at a distance in front of an eye of said patient; and
   processing means for determining when fixation of said pupil on said visual stimulus is lost.

16. The visual field apparatus according to claim 15, wherein said visual stimulus is a moving fixation target.

17. The visual field apparatus according to claim 15, wherein said optical system captures a reflection of said virtual image and said illumination source off said eye, and redirects said reflection onto an imaging system.

18. The visual field apparatus according to claim 17, wherein said optical system includes means for attenuating light reflected from the cornea of said eye.

19. The visual field apparatus according to claim 15, further comprising processing means for monitoring an image of said pupil on an imaging system and for tracking the movement of said pupil in response to said visual stimulus.

20. The visual field apparatus according to claim 15, further comprising an infrared illumination source for illuminating the pupil of said patient.

21. The visual field apparatus according to claim 15, wherein said processing means determines the position of said pupil in each frame using a weighted threshold algorithm.

22.   A method for evaluating the shape of a cornea, said method comprising the steps of:

generating a diagnostic pattern;

projecting a virtual image of said diagnostic pattern at a distance in front of said cornea;

capturing a reflection of said virtual image off said cornea;

directing said reflection onto an imaging system; and

determining the shape of said cornea by comparing said reflected image detected by said imaging system with stored reference information.

23.   The method according to claim 22, wherein said step of generating a diagnostic pattern includes the step of generating one or more concentric rings.

24.   The method according to claim 23, wherein said step of generating a diagnostic pattern includes generating means for differentiating segments of said rings.

25.   The method according to claim 22, further comprising the step of attenuating light scattering off the iris of said eye.

26.   The method according to claim 22, further comprising the step of detecting the pupil in said image, wherein said pupil is detected using an illumination source which is illuminated independently of said diagnostic pattern.

27.   A method of calibrating a corneal topography device, said device consisting of a pattern generator for creating a diagnostic pattern, a centration illumination source for centering and focusing said topography device relative to a patient's cornea, an imaging system and an optical assembly for focusing said pattern at a desired focal point and for directing a reflection of said pattern off an object at a predetermined position relative to said focal point onto said imaging system, said method comprising the steps of:

positioning a calibration sphere approximating the size of a cornea at said predetermined position;

illuminating said sphere with said diagnostic pattern;

creating a first image on said imaging system of a reflection of said pattern off said sphere;

positioning a cursor on said imaging system on approximately the center of said first image;

creating a second image on said imaging system of a reflection of said centration illumination source off said sphere;

adjusting the position of said centration illumination source so that said second image is approximately centered around said cursor; and

storing said first image as a reference image for calculating topographical information about an unknown cornea.

28.   The method according to claim 27, further comprising the step of evaluating the shape of an unknown cornea by subtracting said first image from an image of said cornea to yield an

aberration free image.

29. An apparatus for evaluating the shape of a cornea, said apparatus comprising:
a monochromatic structured light source for generating a diagnostic pattern;
an optical system for capturing a reflection of said diagnostic pattern off said cornea, and for redirecting said reflection onto an imaging system; and
processing means for determining the shape of said cornea by comparing said reflected pattern detected by said imaging system with stored reference information.

30. An apparatus for evaluating the shape of a cornea, said apparatus comprising:
a structured light source for generating a diagnostic pattern;
an optical system for capturing a reflection of said diagnostic pattern off said cornea, and for redirecting said reflection onto an imaging system, said optical system including polarizing means for attenuating light scattering off the iris of said eye; and
processing means for determining the shape of said cornea by comparing said reflected pattern detected by said imaging system with stored reference information.

31. An apparatus for evaluating properties of an eye, said eye including a cornea and a pupil, said apparatus comprising:
a first light source for generating a diagnostic pattern;
a second light source for illuminating said pupil;
means for illuminating said second light source independently of said first light source;
an optical system for capturing a reflection of said illumination off said eye, and for redirecting said reflection onto an imaging system; and
processing means for detecting the location of said pupil by analyzing said reflected illumination.

32. An apparatus for obtaining the topography of an object, comprising:
means for illuminating the object with light that forms a virtual image of a diagnostic pattern a distance behind the object;
means for capturing light reflected from the object; and
means for forming an image from said reflected light, wherein abnormalities in the shape of the object are observed in distortions in the reflected image of the diagnostic pattern.

33. The apparatus of claim 32 further comprising means for processing said reflected image of the diagnostic pattern.

34. The apparatus of claim 33 wherein said means for processing includes means for calculating the radii of curvature of the object along two perpendicular directions.

35. The apparatus of claim 32 wherein said means for

processing includes means for calculating the Gaussian curvature on different points on the object.

36. The apparatus of claim 32 wherein a real image of the diagnostic pattern is formed in front of the object from light reflected therefrom.

37. The apparatus of claim 32 wherein said object is a patient's cornea.

38. The apparatus of claim 32 wherein said diagnostic pattern includes a keratoscope pattern.

39. The apparatus of claim 32 wherein said diagnostic pattern includes a circular checkerboard pattern consisting of concentric circles cut across with radial lines having alternating regions of light and dark.

40. The apparatus of claim 32 wherein said diagnostic pattern is a virtual image.

41. The apparatus of claim 32 further including an aperture stop imaged approximately at the center of curvature of the object.

42. The apparatus of claim 32 further including an exit pupil approximately satisfying the following condition:

$$L = \frac{C_1}{(R_o - r)}$$

wherein L is the location of the exit pupil from the nominal image plane of the diagnostic pattern; C_1 and R_o are positive constants, and r is the radius of curvature of the object.

43. The apparatus of claim 32 wherein said means for processing includes an imaging sensor

44. The apparatus of claim 43 wherein said imaging sensor is a CMOS type imaging sensor.

45. The apparatus of claim 43 wherein said imaging sensor is a charge coupled device (CCD).

46. An optical instrument for measuring the topography of a patient's cornea, comprising:
an optical system for projecting a distance behind the cornea a virtual image of a diagnostic pattern;
means for forming an image of said diagnostic pattern from light reflected from the cornea, wherein abnormalities in the shape of the cornea are observed in distortions in the reflected image of the diagnostic pattern; and
means for processing said distorted image of the diagnostic pattern.

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47. The optical instrument of claim 46 wherein said means for processing includes means for calculating the radii of curvature of the cornea along two perpendicular directions.

48. The optical instrument of claim 46 wherein said means for processing includes means for calculating the Gaussian curvature on different points on the cornea.

49. The optical instrument of claim 46 wherein a real image of the diagnostic pattern is formed in front of the cornea from light reflected therefrom.

50. The optical instrument of claim 46 wherein said diagnostic pattern includes a keratoscope pattern.

51. The optical instrument of claim 46 wherein said diagnostic pattern includes a circular checkerboard pattern consisting of concentric circles cut across with radial lines having alternating regions of light and dark.

52. The optical instrument of claim 46 wherein said diagnostic pattern is a virtual image.

53. The optical instrument of claim 46 wherein said optical system includes a lens refracting light rays of said virtual image to strike substantially perpendicular to the surface of the cornea.

54. The optical instrument of claim 46 further including an exit pupil approximately satisfying the following condition:

$$L = \frac{C_1}{(R_o - r)}$$

wherein L is the location of the exit pupil from the nominal image plane of the diagnostic pattern; C_1 and R_o are positive constants, and r is the base radius of curvature of the cornea.

55. The optical instrument of claim 46 wherein said means for processing includes an imaging sensor.

56. The optical instrument of claim 55 wherein said imaging sensor is a CMOS imaging sensor.

57. The optical instrument of claim 55 wherein said imaging sensor is a charge coupled device (CCD).

58. An apparatus for measuring the topography of a patient's cornea, comprising:
    an optical system for projecting to the cornea a diagnostic pattern, such that light rays from said diagnostic pattern are directed substantially normal to the surface of the cornea; and
    means for forming an image of said diagnostic pattern from light rays reflected from the cornea, wherein abnormalities in the

shape of the cornea are observed in distortions in the reflected image of the diagnostic pattern.

59. The apparatus of claim 58 further comprising means for processing said reflected image of the diagnostic pattern.

60. The apparatus of claim 58 wherein said diagnostic pattern is projected a distance behind the cornea.

61. The apparatus of claim 58 wherein a real image of the diagnostic pattern is formed in front of the cornea from light reflected therefrom.

62. The apparatus of claim 58 wherein said diagnostic pattern includes a keratoscope pattern.

63. The apparatus of claim 58 wherein said diagnostic pattern includes a circular checkerboard pattern consisting of concentric circles cut across with radial lines having alternating regions of light and dark.

64. The apparatus of claim 58 wherein said diagnostic pattern is a virtual image.

65. The apparatus of claim 58 wherein said optical system includes an exit pupil satisfying approximately the following condition:

$$L = \frac{C_1}{(R_o - r)}$$

wherein L is the location of the exit pupil from the nominal image plane of the diagnostic pattern; C_1 and R_o are positive constants, and r is the base radius of curvature of the cornea.

66. An apparatus for measuring the topography of a patient's cornea, comprising:
an optical system for projecting to the cornea a diagnostic pattern, said optical system having an exit pupil, wherein abnormalities in the shape of the cornea are observed in distortions in a reflected image of the diagnostic pattern; and
means for forming an image of said diagnostic pattern from light rays reflected from the cornea, said image located at a first plane for a cornea having a normal base radius of curvature, wherein for radii of curvature deviating from the normal base radius of curvature the location of the exit pupil does not pass through said first plane even though the location thereof shifts from one side of said first plane to the other with variations in the radius of curvature of the cornea.

67. The apparatus of claim 66 further comprising means for processing said distorted image of the diagnostic pattern.

68. The apparatus of claim 66 wherein said diagnostic pattern is projected a distance behind the cornea.

69. The apparatus of claim 66 wherein a real image of the diagnostic pattern is formed in front of the cornea from light reflected therefrom.

70. The apparatus of claim 66 wherein said diagnostic pattern includes a keratoscope pattern.

71. The apparatus of claim 66 wherein said diagnostic pattern includes a circular checkerboard pattern consisting of concentric circles cut across with radial lines having alternating regions of light and dark.

72. The apparatus of claim 66 wherein said diagnostic pattern is a virtual image.

73. A method of obtaining the topography of a patient's cornea comprising the steps of:
    diffusely illuminating the cornea with a first illumination source;
    imaging said first illumination source from light rays reflected from the cornea;
    imaging the pupil and iris of the cornea from light rays passing through the cornea and thereafter reflecting off the iris;
    capturing a composite image of the iris with said first illumination source for outlining the pupil; and then
    illuminating the cornea with a second illumination source for projecting a keratoscope pattern onto the cornea;
    capturing an image of the keratoscope pattern from light rays reflected from the cornea; and
    processing the image of the keratoscope pattern for obtaining the topography of the surface of the cornea.

74. The method of claim 73 further comprising the steps of storing said composite image on a first video frame and storing said image of the keratoscope pattern on a second video frame.

75. An apparatus for measuring the topography of a patient's cornea, comprising:
    an optical system for projecting to the cornea a diagnostic pattern of light and dark regions;
    means for forming an image of said diagnostic pattern from light rays reflected from the cornea, wherein abnormalities in the shape of the cornea are observed in distortions in the reflected image of the diagnostic pattern; and
    means for processing the reflected image of said diagnostic pattern so as to obtain the topography of the surface of the cornea, said optical system having a sufficiently high f-number such that each of the light regions of said diagnostic pattern substantially illuminates only a corresponding region on the cornea.

76. The apparatus of claim 75 wherein said diagnostic pattern is projected a distance behind the cornea.

77. The apparatus of claim 75 wherein a real image of the diagnostic pattern is formed in front of the cornea from light reflected therefrom.

78. The apparatus of claim 75 wherein said diagnostic pattern includes a keratoscope pattern.

79. The apparatus of claim 75 wherein said diagnostic pattern includes a circular checkerboard pattern consisting of concentric circles cut across with radial lines having alternating regions of light and dark.
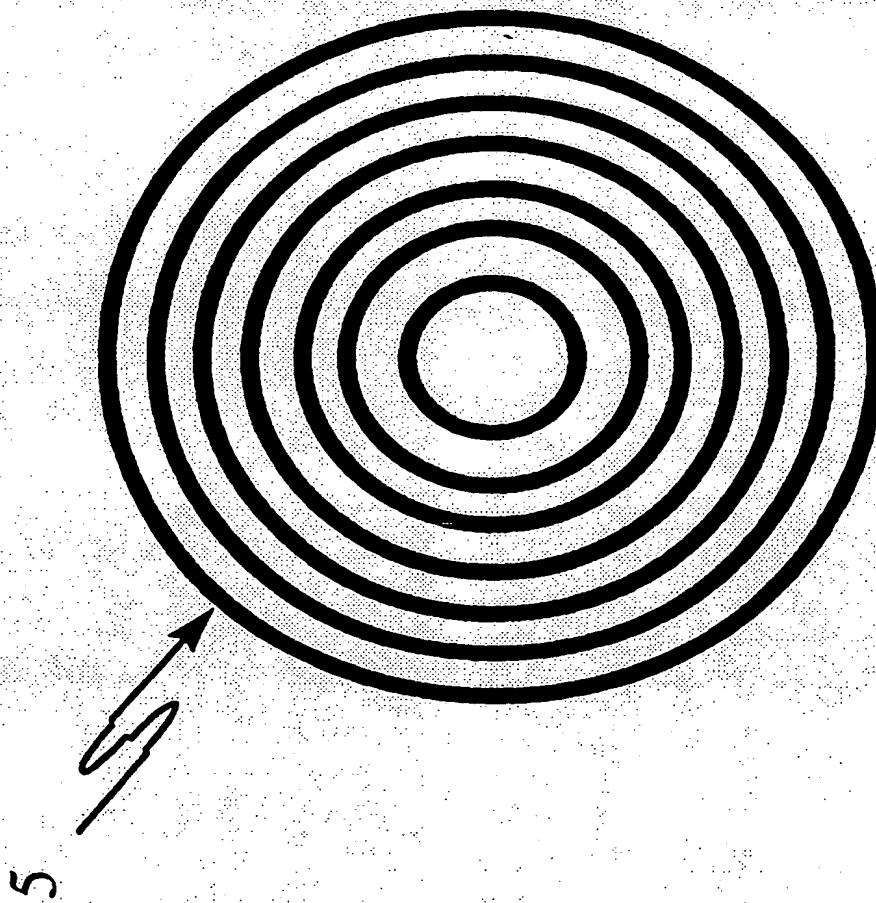
80. The apparatus of claim 75 wherein said diagnostic pattern is a virtual image.

81. The apparatus of claim 75 further including an aperture stop imaged approximately at the nominal center of curvature of the cornea.

82. The apparatus of claim 75 further including an exit pupil approximately satisfying the following condition:

$$L = \frac{C_1}{(R_o - r)}$$

wherein L is the location of the exit pupil from the nominal image plane of the diagnostic pattern; C_1 and R_o are positive constants; and r is the base radius of curvature of the cornea.

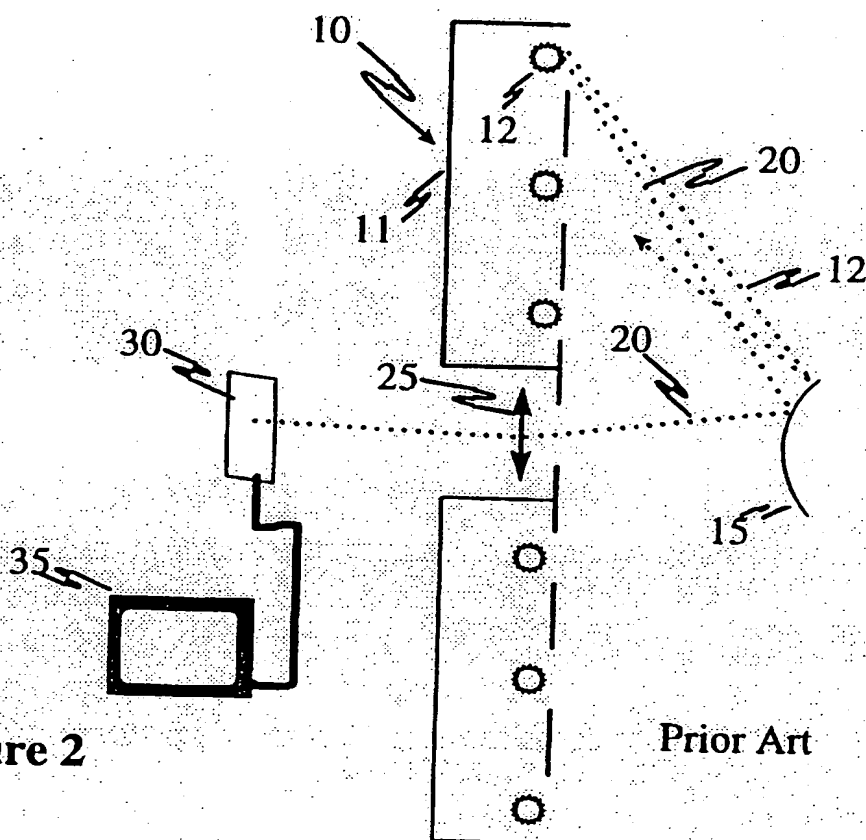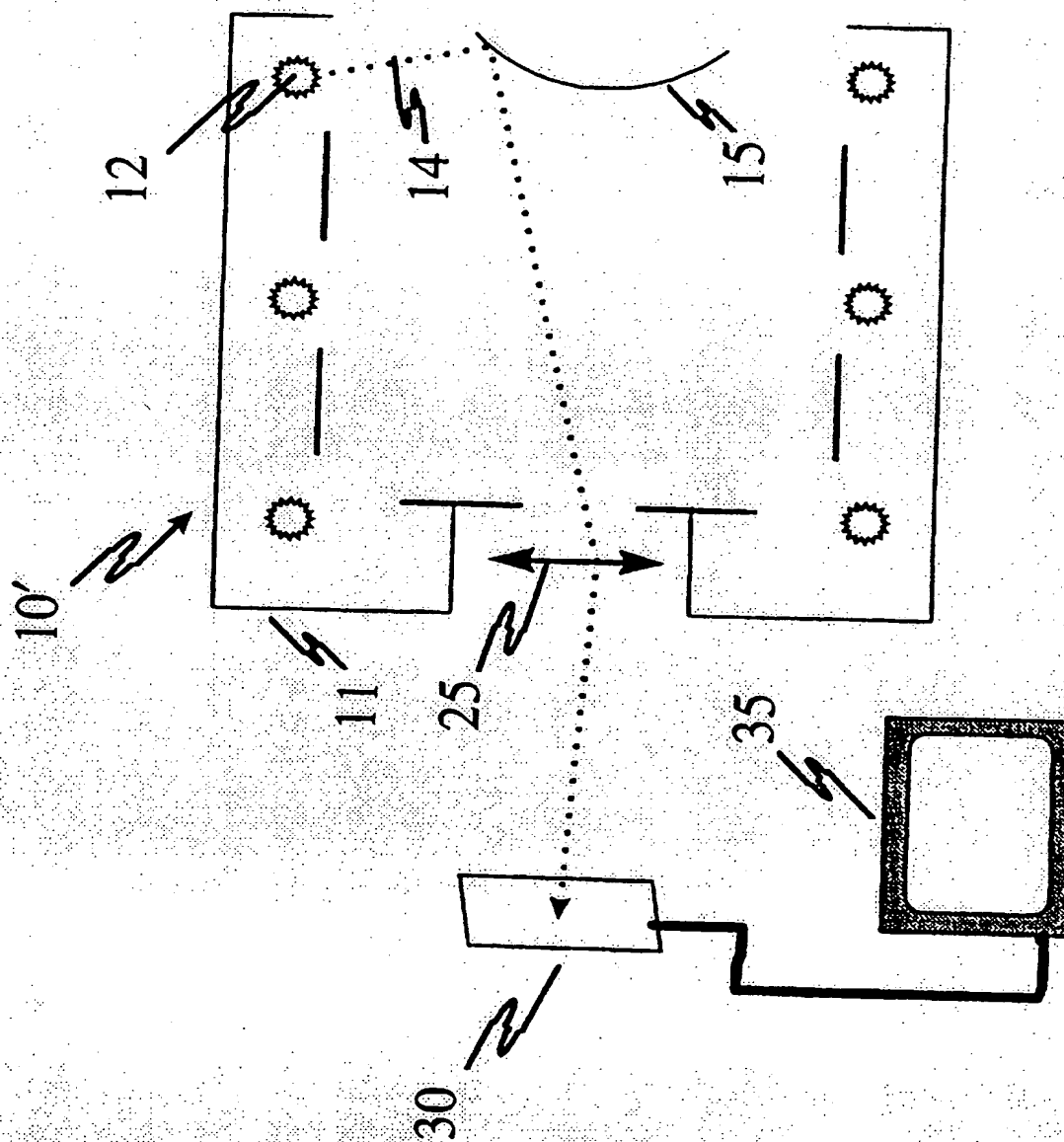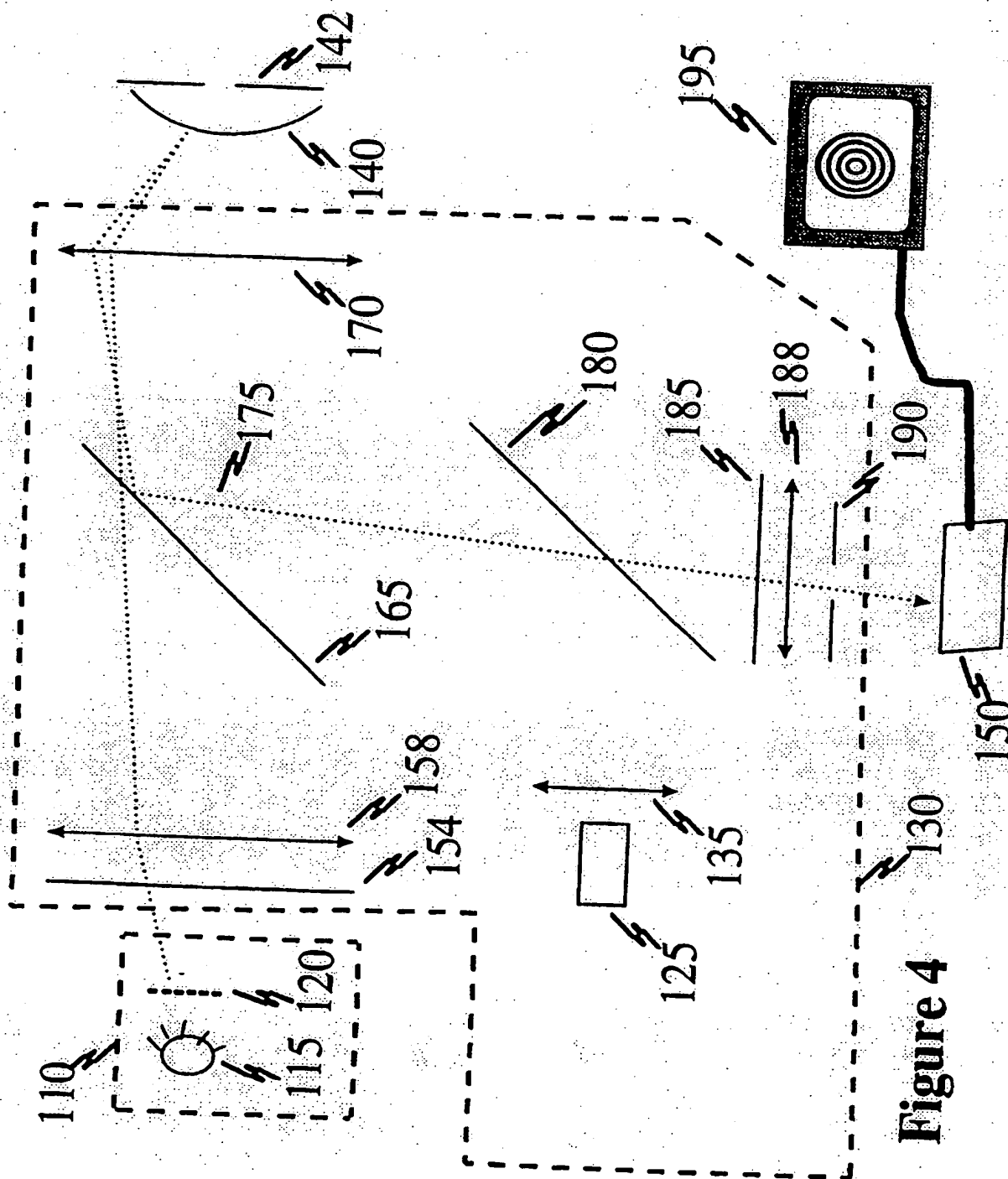83. An apparatus for measuring the topography of a patient's cornea, comprising:
    an optical system for projecting to the cornea a diagnostic pattern of light and dark regions;
    means for forming an image of said diagnostic pattern from light rays reflected from the cornea, wherein abnormalities in the shape of the cornea are observed in distortions in the reflected image of the diagnostic pattern;
    means for illuminating the cornea with a focusing beam;
    a position detector;
    means for imaging onto said position detector a portion of the focusing beam reflected off the cornea, said position detector generating a signal proportional to the position of the reflected focusing beam; and
    means for processing the reflected image of said diagnostic pattern so as to obtain the topography of the surface of the cornea.

84. The apparatus of claim 83 wherein said position detector is a linear position detector.

85.   The apparatus of claim 83 wherein said diagnostic pattern is projected a distance behind the cornea.

86.   The apparatus of claim 83 wherein a real image of the diagnostic pattern is formed in front of the cornea from light reflected therefrom.

87.   The apparatus of claim 83 wherein said diagnostic pattern includes a keratoscope pattern.

88.   The apparatus of claim 83 wherein said diagnostic pattern includes a circular checkerboard pattern consisting of concentric circles cut across with radial lines having alternating regions of light and dark.

89.   The apparatus of claim 83 wherein said diagnostic pattern is a virtual image.

90.   The apparatus of claim 83 wherein said optical system includes an aperture stop imaged approximately at the nominal center of curvature of the cornea.

91.   The apparatus of claim 83 further wherein said optical system includes an exit pupil approximately satisfying the following condition:

$$L = \frac{C_1}{(R_o - r)}$$

wherein L is the location of the exit pupil from the nominal image plane of the diagnostic pattern; C_1 and R_o are positive constants, and r is the base radius of curvature of the cornea.

5

Prior Art

Figure 1

Figure 2

Prior Art

Figure 3

Prior Art

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8A

FIG. 8B

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Figure 9

Figure 10

FIG. 11

FIG. 12